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Soil Science Challenges in a New Era: A Transdisciplinary Overview of Relevant Topics

Jesús Rodrigo-Comino[1,2], Manuel López-Vicente[3], Vinod Kumar[4], Andrés Rodríguez-Seijo[5,6], Orsolya Valkó[7], Claudia Rojas[8,9], Hamid Reza Pourghasemi[10], Luca Salvati[11], Noura Bakr[12], Emmanuelle Vaudour[13], Eric C Brevik[14], Maja Radziemska[15], Manuel Pulido[16], Simone Di Prima[17,18], Marta Dondini[19], Wim de Vries[20], Erika S Santos[21], Maria de Lourdes Mendonça-Santos[22], Yang Yu[23,24] and Panos Panagos[25]

[1]Soil Erosion and Degradation Research Group, Department of Geography, University of Valencia, Valencia, Spain. [2]Physical Geography, Trier University, Trier, Germany. [3]Team Soil, Water and Land Use, Wageningen Environmental Research, Wageningen, The Netherlands. [4]Department of Botany, Government Degree College, Ramban, Ramban, India. [5]Interdisciplinary Centre of Marine and Environmental Research (CIIMAR), University of Porto, Porto, Portugal. [6]Biology Department, Faculty of Sciences, University of Porto, Porto, Portugal. [7]MTA-ÖK Lendület Seed Ecology Research Group, Institute of Ecology and Botany, Centre for Ecological Research, Vácrátót, Hungary. [8]Laboratory of Soil Microbial Ecology and Biogeochemistry, Institute of Agri-Food, Animal and Environmental Sciences (ICA3), Universidad de O'Higgins, San Fernando, Chile. [9]Center of Applied Ecology and Sustainability (CAPES), Santiago, Chile. [10]Department of Natural Resources and Environmental Engineering, College of Agriculture, Shiraz University, Shiraz, Iran. [11]Department of Economics and Law, University of Macerata, Macerata, Italy. [12]Soils and Water Use Department, National Research Centre, Cairo, Egypt. [13]Université Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS, Thiverval-Grignon, France. [14]Departments of Natural Sciences and Agriculture and Technical Studies, Dickinson State University, Dickinson, ND, USA. [15]Department of Environmental Improvement, Faculty of Civil and Environmental Engineering, Warsaw University of Life Sciences, Warsaw, Poland. [16]GeoEnvironmental Research Group, University of Extremadura, Cáceres, Spain. [17]Department of Agricultural Sciences, University of Sassari, Sassari, Italy. [18]Univ Lyon, Université Claude Bernard Lyon 1, CNRS, ENTPE, UMR 5023 LEHNA, Vaulx-en-Velin, France. [19]Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen, UK. [20]Environmental Systems Analysis Group, Wageningen University and Research, Wageningen, The Netherlands. [21]Linking Landscape, Environment, Agriculture and Food Research Centre, Instituto Superior de Agronomia, Universidade de Lisboa, Lisbon, Portugal. [22]EMBRAPA—Brazilian Agricultural Research Corporation, CPACP (Embrapa Cocais), São Luís, Brazil. [23]College of Soil and Water Conservation, Beijing Forestry University, Beijing, China. [24]Jixian National Forest Ecosystem Research Network Station, CNERN, Beijing Forestry University, Beijing, China. [25]Joint Research Centre (JRC), European Commission, Ispra, Italy.

ABSTRACT: Transdisciplinary approaches that provide holistic views are essential to properly understand soil processes and the importance of soil to society and will be crucial in the future to integrate distinct disciplines into soil studies. A myriad of challenges faces soil science at the beginning of the 2020s. The main aim of this overview is to assess past achievements and current challenges regarding soil threats such as erosion and soil contamination related to different United Nations sustainable development goals (SDGs) including (1) sustainable food production, (2) ensure healthy lives and reduce environmental risks (SDG3), (3) ensure water availability (SDG6), and (4) enhanced soil carbon sequestration because of climate change (SDG13). Twenty experts from different disciplines related to soil sciences offer perspectives on important research directions. Special attention must be paid to some concerns such as (1) effective soil conservation strategies; (2) new computational technologies, models, and in situ measurements that will bring new insights to in-soil process at spatiotemporal scales, their relationships, dynamics, and thresholds; (3) impacts of human activities, wildfires, and climate change on soil microorganisms and thereby on biogeochemical cycles and water relationships; (4) microplastics as a new potential pollutant; (5) the development of green technologies for soil rehabilitation; and (6) the reduction of greenhouse gas emissions by simultaneous soil carbon sequestration and reduction in nitrous oxide emission. Manuscripts on topics such as these are particularly welcomed in *Air, Soil and Water Research*.

KEYWORDS: Soil research, degradation, biogeochemical cycles, rehabilitation, soil and human health, soil modeling

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CORRESPONDING AUTHOR: Jesús Rodrigo-Comino, Soil Erosion and Degradation Research Group, Department of Geography, University of Valencia, 46010 Valencia, Spain. Email: rodrigo-comino@uma.es

Introduction

Past, current, and, presumably, future scientific literature has and will include studies related to soils. Soils are a vital life sphere that can generate indispensable resources and goods to supply natural and human ecosystems.[1,2] The numerous biogeochemical cycles and different interactions among spheres (atmosphere, geosphere, biosphere, anthroposphere, hydrosphere) all converge into the pedosphere. Moreover, climate change, intensification of agricultural activities, urbanization, military conflicts, mining and other industrial activities and associated infrastructures for transport, such as roads and railroads among others, have affected soils over many centuries. However, these have become more and more intense during the last two decades, threatening the few spots that still have natural relatively unaltered soils.[3-5] Therefore, it is inevitable that more literature will be published in the coming years and more fieldwork will be conducted (Figure 1), with more advanced modeling and data analysis techniques expected to be applied to soil issues. It is necessary to increasingly experience relevant debates about soil concepts that are widely applied in novel investigations by pioneering scientists. For example, scientific and technological work is advancing on soil quality and soil quality indicators,[6,7] soil resilience from a sustainable perspective,[8] soil degradation,[9] soil and human health and security,[10] soil rehabilitation,[11] or land degradation neutrality.[12] Immersed in a globalized and capitalistic economic system, developing research in soil science should consider the costs of soil conservation and the value of benefits provided by soil services (eg, water filtration, carbon sequestration, supplying food, fuel, and shelter). Besides, the application of specific control measures should be a premise to put value in these studies for stakeholders, policymakers, and for all of society.

Soil sciences have acquired a very special relevance in recent decades. The United Nations (UN), both directly in different reports, and through the sustainable development goals (SDGs), has set the highest level of transdisciplinarity for soil sciences. There are several emerging societal research challenges, as described in the UN SDGs (https://sustainabledevelopment.un.org/?menu=130) that are linked to soil quality aspects such as (1) SDG 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture; (2) SDG 3: Ensure healthy lives and promote well-being for all at all ages (non-communicable diseases, mental health and environmental risks); (3) SDG 6: Ensure availability and sustainable management of water and sanitation for all; (4) SDG 13: Take urgent action to combat climate change and its impacts and (5) SDG 15: Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. These SDGs are connected to specific soil science challenges, including (1) sustainable food production, referring to proper nutrient management, avoiding or reducing soil threats, such as soil erosion, soil acidification, soil compaction, and soil biodiversity impacts, and reducing environmental impacts on air and water quality (SDG2 and SDG15); (2) solving soil pollution problems, related to metals/metalloids, pesticides and other organic components, microplastics, and emerging pollutants (SDG3); (3) enhancing the water storage and filtering/buffer capacity of soils (SDG6); and (4) enhanced soil carbon sequestration and reducing soil nitrous oxide emissions because of climate change (SDG13). Note that these challenges are also interrelated. For example, soil carbon sequestration enhances soil water and nutrient retention and organic pollutant decay.

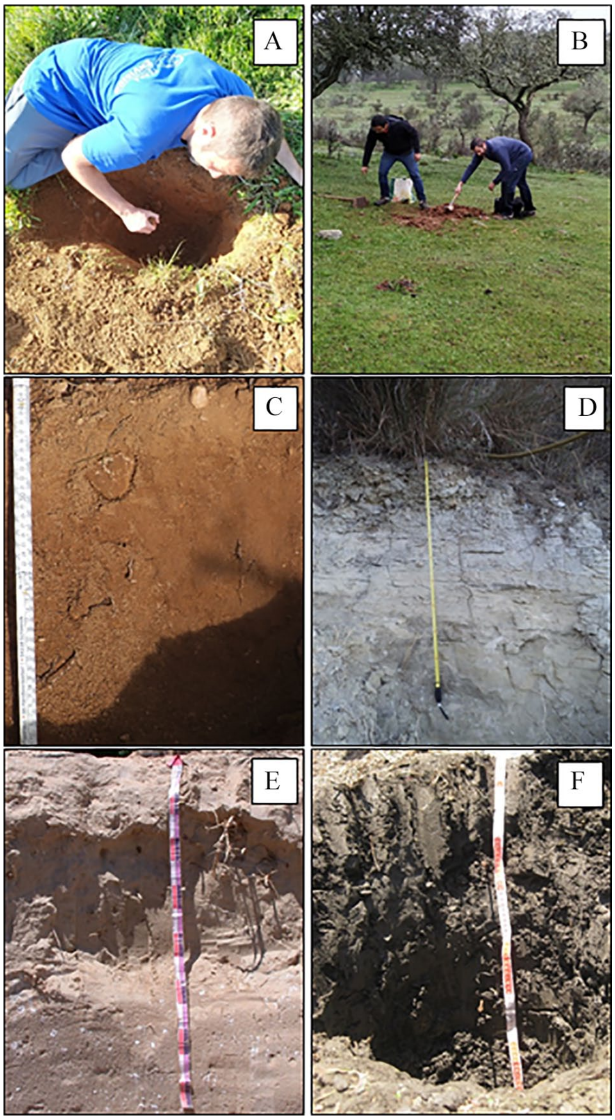

Figure 1. Soil scientists and soil profiles: (A and B) Dr Manuel Pulido performing soil bulk density measurements; (C) Terric Anthrosol with colluvic materials[1] in the vineyards of the Celler del Roure, Valencia, Spain; (D) Eutric Gypsisol,[1] Málaga city, Spain; (E) Entisols[2] soil order with calcium carbonate concretions in deep horizon, Western desert, Egypt; (F) Aridisols[2] soil order with vertic features (slickenside, wedge-shaped aggregates, and high clay content), Northern Nile Delta, Egypt. Photos were taken by Jesús Barrena and Manuel Pulido (Extremadura University), Jesús Rodrigo-Comino (Valencia and Trier Universities), and Noura Bakr (National Research Centre, Cairo).

This article aims to give a succinct overview of soil science challenges related to the above-mentioned societal perspectives and discuss possible steps forward. In this article, several examples of relevant soil threats and soil functions that pose challenges for soil research are presented, but it also opens the debate to colleagues for new challenges and topics to be addressed. To achieve this goal, 20 experts from the editorial team of *Air, Soil and Water Research* (SAGE; https://journals.sagepub.com/home/asw), with backgrounds in multiple disciplines such as geography, soil science, geology, agronomy, biology, environmental sciences, engineering, ecology, cartography and remote sensing, present overviews of a selection of current and relevant topics related to soil. Five major topics were addressed: soil and human health, soil biodiversity and threats, soil and water systems, soil digital mapping, and soil organic carbon sequestration.

Soil Bioremediation and Human Health

Soils have an impact on human health, both directly and indirectly. Soils supply nutrients essential to overall organisms and human life that are passed up the food chain from the soil through the plant to the consumer and they supply medications from inorganic and organic compounds, and organisms. However, contamination of soil may be a cause for human disease in cases of high exposure to metals/metalloids, organic chemicals, soil pathogens, and radionuclides. Several recent articles have summarized the ways that soils influence human health.[13-16] Despite the progress that has been made in unraveling the linkage between soil contamination and human health, there are still many areas that need additional investigation, such as enhanced understanding of how chemical mixtures in the environment influence human health, and the linkage between soil ecology and human health via crop production and nutrition, as discussed in articles such as Brevik et al[17] and Oliver and Gregory.[18] One of the promising ways to address the potential negative effects of soil pollution on human health can be through bioremediation, with/without considering other technologies.

The negative effects of human activity on the Earth's surface have been the most severe in urban, industrial, and agricultural areas (Figure 2).[19,20] Increased ecological awareness by society plays an increasingly significant role in expanding successful methods of remediating degraded areas. Contaminants, independently of the typology, with adverse effects on the natural environment and human health have an increasingly global character, though their effect is observed at a local level in many cases. It is very important to seek out innovative solutions regarding polluted areas, where activities connected with bioremediation, which are safer and interfere less with the natural environment than to other methods, have been gaining increasing significance. One of the main aims of introducing bioremediation treatments to degraded areas is to prevent the migration of contaminants into the food chain where they could pose a threat to human health.[21] There are many technologies for the bioremediation of contaminated areas.

Bioremediation is an interesting but not really new concept. Also, previous studies have shown that in some cases inorganic pollutant uptake from the soil by plants was much smaller than expected.[22,23] Uptake was too small to be of practical use in some cases, in order to reach pre-contamination levels over a reasonable amount of remediation time.[24] However, the situation has changed over the last 20 years considering new advances, but it is certainly worth taking a close look at the relevant literature to see that much work is still needed.[25,26] In general, bioremediation has potential applications in, eg, degradation of organic contaminant, removing potentially toxic or hazardous elements from water and soil and the extraction/leaching of metals/metalloids from ores, as well as solid, liquid and gaseous wastes.[27] Among the different techniques of in situ, namely with plants, bioremediation is phytostabilization, which can be used in highly contaminated areas located in distinct climatic conditions and even in the presence of multi-elemental contamination (following the Environmental Protection Agency, and the report: Introduction to Phytoremediation EPA/600/R-99/107). This technology makes use of plants with/without various types of amendments, changing the properties of the soil to decrease the bioavailability of toxic elements. The function of plants, in this case, is connected with the absorption and accumulation of toxic elements in roots and/or precipitation or adsorption on the surface of the roots.[28] Moreover, plants can also influence some changes in the chemical form of some trace elements and promote the precipitation and complexation of contaminants by altering soil properties, such as pH or oxidation-reduction potential, for instance by exudation of protons, hydroxyl ions, and/or organic acids. Phytostabilization is a technology of diminishing the impact of the contaminated areas on the surrounding ecosystem and reducing the introduction of potential contaminants into the food chain. Moreover, plant development can improve other characteristics of the degraded soils such as structure, fertility, microbiota activity, and diversity, and control leaching as well as wind and water erosion.[29,30] Nonetheless, in some scenarios of soil contamination and/or climatic conditions, the development of the vegetation directly on contaminated soils can be very difficult and the growth very slowly so, the obtaining of positive effects on chemical and biological parameters of contaminated soils can be delayed.

It is important to perform long-term monitoring to avoid unfavorable and unexpected effects from bioremediation. The application of phytostabilization does not have to be the final method of managing the contaminated area, but merely an intermediate means of protection against the migration of contaminants until other methods act simultaneously in the rehabilitation are developed. Scientific literature from recent years contains many examples of studies and experiments achieved in this field.[31,32] These actions represent positive steps in protecting the surface of the Earth and human health; however, one question remains: Why those methods have not already been applied in an extensive way to remediate polluted soils? As mentioned above, bioremediation has been explored and tested in the past and was deemed not practical in some cases due to the inexistence of known tolerant plant species, low uptake rate, long time investment, and therefore prohibitive costs (at least in terms of

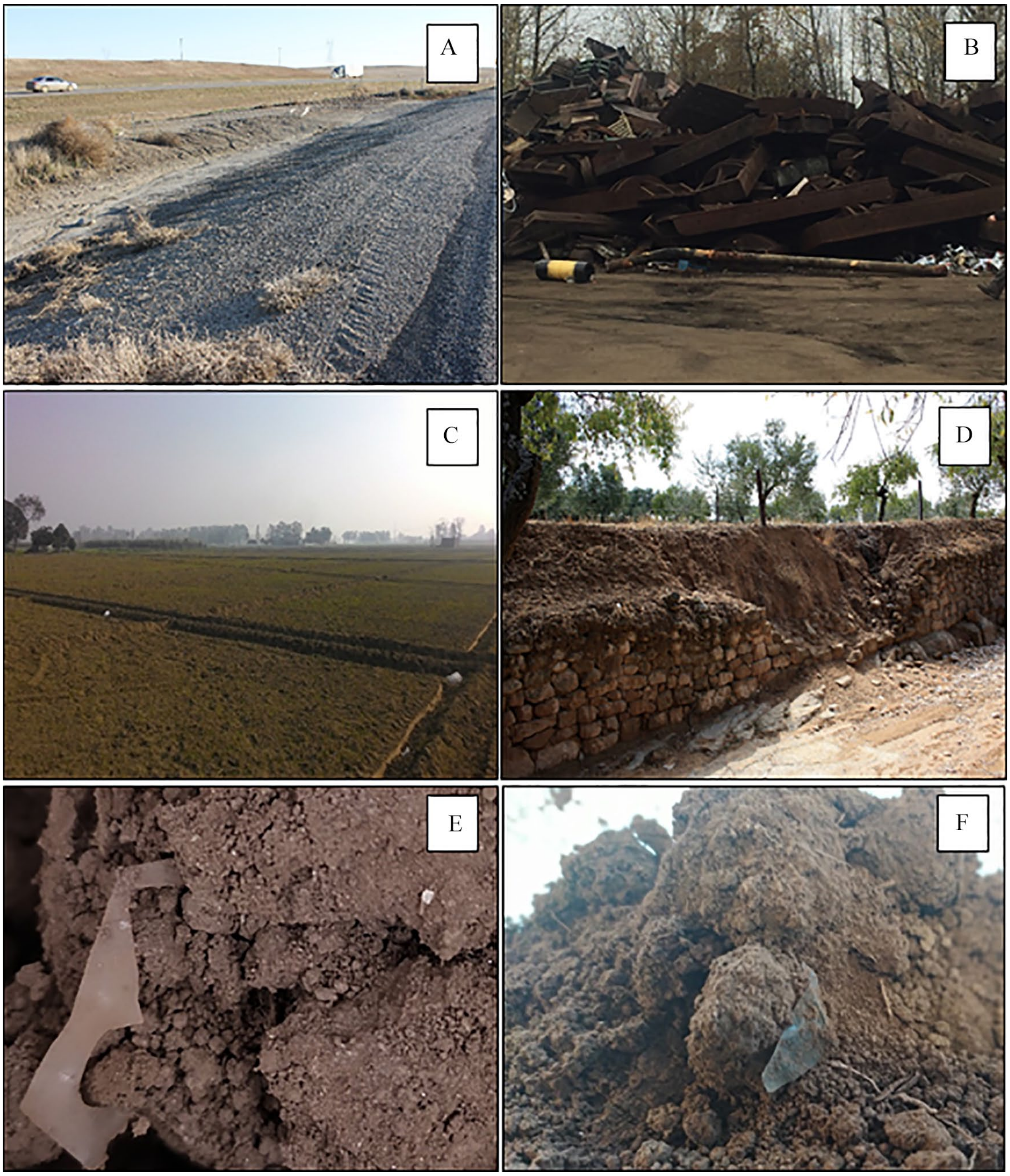

Figure 2. Soil degradation by contamination and overexploitation: (A) soil contaminated with jet fuel and pesticides, North Dakota, USA; (B) contamination from an iron and steel scrap storage yard, central Poland; (C) irrigated and tilled fields in Jalandhar, Punjab, India; (D) agricultural terraces in abandoned fields in Bierge, Spain; (E and F) plastic items found in soils from an old greenhouse field, Portugal. Photos were taken by Eric C. Brevik (Dickinson State University), Maja Radziemska (Warsaw University of Life Sciences), Manuel López-Vicente (Wageningen University), and Andrés Rodríguez-Seijo (University of Porto).

metals/metalloid uptake using plants). However, the scientific community should not advocate abandoning the idea of bioremediation. Finally, emergencies such as the current COVID-19 pandemic may create new prioritization in research and exploring linkages between soils and human health considering the increasing literature recently published.[33-35]

Soil Biodiversity and Threats

Soils are one of the most diverse habitats on Earth. A single gram of soil can host billions of cells, distributed in tens of thousands of species of bacteria and on the order of thousands of different species of fungi.[36] In addition, invertebrate species span from the order of hundreds to thousands of species per square meter in organic-rich soils.[37] Soils constitute the habitat for the organisms that inhabit them for a selected period or throughout their entire life cycle. For example, the majority of the terrestrial insect species spend at least some of their life stages in soil, and for most terrestrial plants, the soil is the most important substrate. This edaphic life can be classified according to body size, including microorganisms (μm scale), microfauna (<0.1 mm),

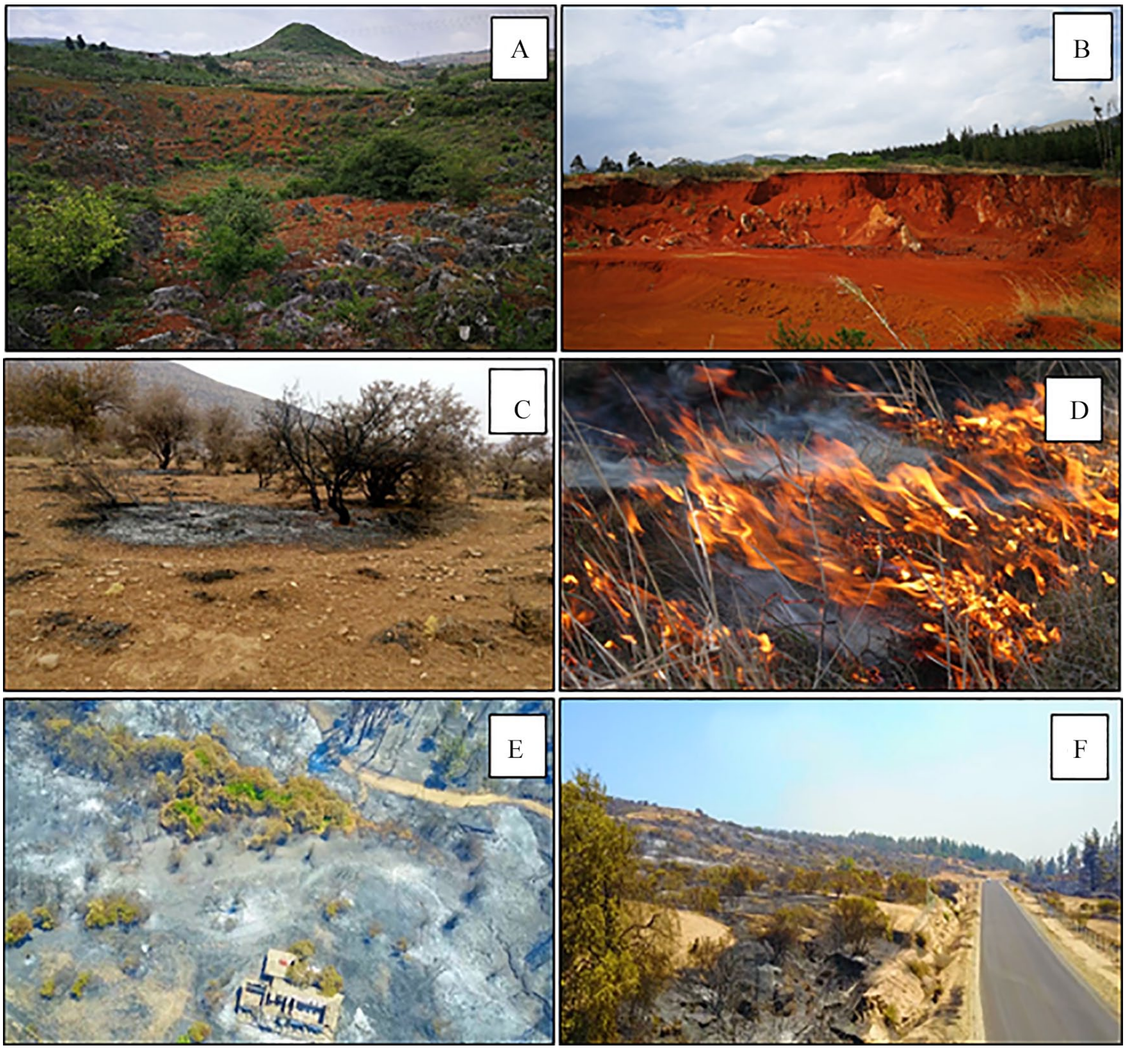

Figure 3. Wildfire effects on soil: (A and B) A landscape of Karst Garbin Basin (Xibeile Town, Mengzi City, Yunnan Province) where took place the field experiment for restoration areas (2016-2020); (C) non-rehabilitated burned soils in Fars, Iran; (D) grassland wildfire, Karcag, Hungary; (E and F) January-February 2017 at Pumanque, Chile. Photos were taken by Hamid Reza Pourghasemi (Shiraz University), Orsolya Valkó (Hungarian Academy of Sciences), Daniel Bahamondes (Universidad de O'Higgins), and Yang Yu (Beijing Forestry University).

mesofauna (0.1-2.0 mm), macrofauna (2-20 mm), and megafauna (>20 mm),[38] all of which are fundamental to support soil ecosystem functions. Microorganisms, including bacteria, archaea, and fungi, are the most important group driving biogeochemical processes. Still, their complex contribution to edaphic functions is yet to be fully understood and most of them are currently unculturable and not described.[39,40]

Giller et al[41,42] stated the necessity of deeper investigations into the interactions between belowground diversity and stability of ecosystem functions to develop a mechanistic understanding of anthropogenic effects on soil biota. To achieve a mechanistic understanding, standardization of protocols for sampling, extraction, and determination is essential to evaluate and compare biodiversity from the pedon to larger scales.[37,43] There are several challenges to be solved in soil biodiversity monitoring programs related to taxonomic classification, biodiversity indices, and the selection of key species affected by the elevated number of activities and degrees of negative impact. This is also key to develop efficient restoration plans in areas with arid and semi-arid climates, hilly catchments, or poor soils such as the karst areas in the Loess Plateau (Figure 3A and B), highly affected by land degradation processes.[44,45]

Below an overview of 3 emerging threat factors to soil biodiversity are presented, namely potentially toxic elements and solutions for mitigating their negative effects using green technologies, wildfires, and microplastics.

Potentially toxic elements

Several anthropic activities are hotspots of environmental contamination, with soil often being the most affected natural resource. It is well known that the concentrations of potentially toxic elements (PTE) in the soil can vary significantly over spatial and temporal scales, even within the same studied area. Moreover, in many contaminated areas, the drivers of environmental degradation go beyond the PTE concentrations in total and available fractions (eg, loss of soil structure and fertility, acidification/alkalinization, and/or decrease of specific and functional diversity). Also, it is worth highlighting the different biogeochemical behaviors of metals, metalloids, and anions, which are oftentimes overlooked. The coexistence of several degradation factors (eg, loss of soil structure and fertility, acidification/alkalinization and/or decrease of specific and functional diversity) amplifies the complexity of the problem, complicating its rehabilitation.[46-48]

Major producers of PTE include human activities such as agriculture, industry, mining, tourism, and urbanization,[49,50] which directly affect soil health, fertility, quality, and the carbon cycle.[51,52] Nowadays, we do not have a clear understanding of the potential differences between potentially hazardous or toxic elements sources from the various anthropogenic activities that release them into the environment, such as industrial, domestic, and agronomic aspects. These activities include the use of pesticides, fertilizers, herbicides, industrial activities, wastewater, sludge, disposal of medical wastes, mining, and so forth,[53-55] and natural processes such as geogenic sources and weathering of rocks.[56,57] Among the PTEs, metals and metalloids (eg, As and Sb) are toxic to most microorganisms and fauna when they occur in high concentrations,[41,58] some of them even in small concentrations, and represent a grave problem in soils not only in specific regions but throughout the world.[59]

A usual approach to the risk assessment of contaminated soils is based on the comparison of the total concentrations of PTE to critical concentrations, which are often simply based on the background the established concentrations per country or regions[60] which often do not take into account the local geochemical background. It is well known that the estimation of these pollutants and their concentration alone do not give an accurate pollution status in soils, water, and sediments. Only the elements included in the soil solution and associated with the exchange complex of inorganic and organic soil colloids are available to the organisms and biogeochemical cycles. To better estimate the pollution or contamination level from anthropic and natural processes, the application of contamination or pollution indices is necessary. The various indices, such as contamination factor (CF), enrichment factor (EF), pollution load index (PLI), geo-accumulation index (Igeo), potential contamination index (Cp), pollution index (PI), modified pollution index (MPI), potential ecological risk index (RI), and modified potential ecological risk index (MPI) can provide a meticulous assessment of contamination risk status for soils. However, more work must be done to standardize the input data and consider the spatiotemporal variability depending on each land-use system and soil characteristics. Besides the economic costs of remediation, the effectiveness of rehabilitation and conservation practices need additional investigation.

Wildfires

Although wildfires are natural disturbances that can occur in any terrestrial ecosystem, the current increase in fire intensity and severity in the era of accelerated climate change endangers the resilience of these habitats. Every year, approximately 4% of the global land surface burns.[61] Some examples of wildfires and the resulting degraded soils are shown in Figure 3, including examples from Iran (Figure 3C), Hungary (Figure 3D), and Chile (Figure 3E and 3F). The two major parameters that determine the ignition of fire are the availability of flammable fuel and the proper climatic conditions that allow ignition. As both are highly affected by global climatic and land-use changes, modern fire regimes are changing, and in many regions, the frequency, extent, and severity of fires are expected to increase in the future.[62] The effects of fires on soil properties depend primarily on pre-fire edaphic conditions, the type of ecosystem affected, the severity and intensity of the fire, and post-fire meteorological conditions.[63] The negative effect of fires on soil properties is well recognized, and the greater sensitivity of soil biological properties to disturbances (compared with abiotic conditions) has also been established.[64,65] Although soil biological processes are recognized as main drivers of ecosystem recovery following fires, the consequences of wildfires on soil biota are less understood than the effects on soil physicochemical properties.[66] To cope with this globally relevant issue, and minimize the negative impact of fire on soil, major advances in science, management, and policy regarding soil biodiversity and ecosystem services are needed. Given the current scenario, finding feasible solutions, particularly those based on nature, is especially important to cope with the global fire crisis. In this sense, restoration approaches should focus on improvements of belowground conditions, a key component to sustaining aboveground recovery and succession following soil disturbances.[39,67]

The major challenges and future needs for understanding and mitigating fire effects on soil biodiversity are as follows. (1) For effective conservation of soil systems and the ecosystem services they provide, it is necessary to understand the effect of fire regimes on soil and identify potential threats. Possibilities in the application of prescribed burning to maintain ecosystems also need to be explored.[68] (2) As most biodiversity research focuses on aboveground diversity, the understanding of most ecological processes and biodiversity patterns is biased, as belowground biodiversity research is largely underrepresented in the literature,[37] and belowground macroorganism diversity is underrepresented as compared with microorganism diversity.[18] In the future, more research should target the exploration of belowground soil biodiversity and the response of soil biota to global changes in climate, land use, and fire regimes, which could support the development of policies targeting the protection of soil biodiversity. (3) A stronger link should be established between aboveground and belowground biodiversity and ecosystem functioning[69,70] to tackle the effects of global drivers, such as fire regimes, climate, and land use on the stability of ecosystems. (4) Post-fire rehabilitation measures need to be developed to support the recovery of fire-affected soil systems.[71]

Microplastics: an increasingly important environmental issue that requires our attention concerning soils

The development of the plastic polymers that are widely used today took place between 1930 and 1950. Their massive introduction to the market at the end of the 1980s was an industrial and commercial revolution. These new versatile materials, with their higher durability, electrical resistance, plasticity, and especially their low cost of production, made them crucial and sometimes almost irreplaceable in our daily lives (Figure 2E and 2 F). More than 359 million tons of plastics are produced globally per year, and up to 40% of those plastics are packaging and single-use plastics with a short lifespan (approximately 50% of plastics have a service life between 10 minutes and 30 days). These represent serious environmental issues, as waste management technology has not increased at the same rate as plastic production and use[72,73] and changes in consumption habits are still in the first stages. The impact of microplastics on soil biodiversity is thus an increasingly important environmental issue that requires our attention in soil science.

Once in the environment, plastics undergo degradation when exposed to physical, chemical, or biological factors (eg, UV radiation, mechanical abrasion, temperature, moisture, redox conditions). Degradation results in small particles of plastic of irregular shape and size (usually < 5 mm) called "microplastics" (MP), which are the main form of plastic debris found in the environment. These MP can easily be dispersed, enter food webs and damage organisms, and potentially affect several ecosystem functions. While the impact of MP in aquatic ecosystems is widely known with the first studies occurring in the 1970s, knowledge of the effects of MP on soil systems is still recent (less than 10 years).[73-75] Studies that have been conducted have investigated the impacts of MP on soil physicochemical properties (bulk density, soil structure, etc) or soil fauna (eg, earthworms, collembolan).[76-78] Adverse impacts on terrestrial plants and soil microbial activities have recently been reviewed, but the knowledge is limited, especially concerning soil (micro-)organisms and the interactions between MP and soil properties.[79] In general, long-term contamination by plastic film residues has been correlated with the inhibition of soil microbial activity and fertility due to changes in the activity of enzymes involved in C, N, and P biogeochemical cycles. However, the study of the interaction of MP with the soil microbial community has received little attention to this time.[80-82] It has also been pointed out that plastics could act as carriers of inorganic and organic contaminants in the water-soil interface, releasing these contaminants into the environment and affecting soil (micro-)organisms, with adverse consequences for the food web.[83,84]

As a result of increased environmental awareness, biodegradable, oxo-biodegradable, and compostable plastics have been proposed as environmentally friendly alternatives to conventional plastics.[85,86] However, the ecotoxicological implications of these materials are not well studied or they have sometimes been reported to have unanticipated problems such as low environmental degradation under realistic conditions.[86] Thus, there are some knowledge gaps on the occurrence and environmental impact of MP in terrestrial ecosystems that need urgent attention to inform changes in the policies that address and regulate the use and disposal of plastic: (1) the identification of potential sources of MP contamination (eg, agricultural irrigation using wastewater, tire abrasion, or microfibers released after washing), (2) mobility and degradation of MP in the soil under field conditions, (3) ingestion of plastic fibers by soil organisms, (4) understanding the impact of global warming and soil characteristics on the biodegradation rate of plastic polymers, and (5) developing adequate techniques for the extraction and identification of these materials in soils, as current techniques have several issues.

Finally, during the COVID-19 pandemic use of disposable face masks (produced from polymers) is one of the most relevant precautionary measures. The most recent publications claim that the increase in production/consumption of this product is adding a large amount of plastic and plastic particle waste to the environment, reaching waterways[87] (freshwater and marine environments) and the surrounding soils.[88,89] This will be another key challenge related to microplastics and soil pollution for the scientific community in this new era.[90]

Integrated rehabilitation of degraded areas using green technologies

Several degraded soils are non-productive and incapable of generating the ecosystem functions and economic profitability necessary for their recovery.[91] Although governmental and other public/private entities recognize the importance of rehabilitating these areas, the conventional techniques usually applied are limited at the environmental level, because they only act on a few parameters of the medium (eg, increase of pH or organic matter), giving a partial solution.[92] Therefore, more research is necessary for this area. Besides the environmental effectiveness, economic evaluation, especially in the initial implementation, is important in selecting a rehabilitation strategy.[93,94]

For successful rehabilitation of a system as a whole, the design and application of strategies adapted to the characteristics of each area that integrate the different components of the ecosystem and their interrelations, coexistence of all degradation factors, the new land use, and the cost and technical efficiency need to be tested. Moreover, it is important to develop and apply sustainable and green technologies, which are increasingly favored (eg, phytodegradation, phytovolatilization, phytoextraction, etc). A combination of green technologies, that may or may not be incorporated into a designed Technosol with phytostabilization, has been demonstrated to be cost-effective in the integrated remediation of contaminated areas at the laboratory, micro-, and mesocosm scales under controlled conditions.[95-97] This is due to the simultaneous action on several biogeochemical processes; some of them are complimentary and involved in the environmental rehabilitation process.

The use of different so-called green technologies (the "greenness" of which sometimes still has to be demonstrated, in terms of energetic balance) and heterogeneity of the environmental problem would be key.[98] Combined methods may also accelerate the rehabilitation processes. Nowadays, some international business groups and governmental entities from several countries are considering and in some cases (little by little) implementing this new approach in their operational and closure activities.[99,100] Sharing information from case studies where new and integrated approaches are used, including levels of environmental improvements and associated costs, is essential to improving our knowledge of these technologies.

Soil and Water Interactions

The nexus between soil, water, energy, and food has recently evolved as a resource-management concept to deal with this intimately interwoven set of resources, their complex interactions, and the growing and continuously changing internal and external sets of influencing factors including climate change, population growth, habits, and lifestyle alterations. At the heart of those complex interactions, soil health and water conservation have emerged as global challenges in a world where pressures from growing demands and shrinking supplies have reached a critical junction for several major global resources, particularly water, energy, and food. To address those challenges, the science community is increasingly challenged with finding more accurate methods of modeling water and nutrient/pollutant distributions in natural, agricultural, forestry, and urban soils to sustain healthy soils, preserve water resources, and secure sustainable food supply for the 7.8 billion inhabitants of this planet.

Soil water and hydrology

The quality of groundwater is highly dependent on soils' ability to infiltrate and filter stormwater and rainwater, thereby removing contaminants. Modeling this ability is dependent on our ability to characterize the complex and heterogeneous nature of soils and the filtration processes. Water recharge processes can be divided into slow uniform movements of water through smaller pores, and fast non-uniform water movement along larger and more active pathways referred to as preferential flow.[101] Preferential flow can contribute to the rapid transport of contaminants from the soil surface into receiving streams, bypassing the filtering capacity of the soil.[102] Developing appropriate approaches to study preferential water movement is a prerequisite to understanding groundwater recharge processes. Preferential flow and its consequences for (contaminant) transport have been studied for decades by soil physicists, soil chemists, and (hydro-)geologists. The fundamental understanding of how preferential flow works has been largely developed. There is, however, still no silver bullet to model preferential flow, storage processes, and related contaminant transport.[103]

Several models were developed by the scientific community in the last few decades for interpreting and simulating soil water processes. They are fundamental to gain insight into (1) water and nutrients available for plant root systems from the perspective of sustainable agriculture in widely different environments; (2) understanding point or diffuse pollution of aquifers; (3) water conservation, losses and salinity issues in arid environments; (4) soil water erosion; and (5) management of soil structure in urban environments.[104-106] These models rely on soil hydraulic properties that are incorporated into two fundamental characteristics: (1) the soil water retention curve $\theta(h)$, describing the relationship between volumetric soil water content, θ (L3 L-3), and soil water pressure head, h (L); and (2) the hydraulic conductivity function, $K(\theta)$ or $K(h)$, describing the relationship between θ or h and soil hydraulic conductivity, K (L T-1).[107]

Many studies have focused on the development of methods for predicting or measuring soil hydraulic characteristics. The predictive methods allow estimation of soil hydraulic parameters through empirical relationships (pedo-transfer functions [PTFs]) from more widely available data (eg, texture, bulk density). However, the PTFs often rely on site-specific statistical regression equations; thus, they may lack generality.[108] The direct measurement techniques are generally difficult to apply over large areas and are mainly devoted to the field scale. They include either laboratory- or field-based procedures. The former ones allow accurate measurement of flow processes, but they can induce experimental artifacts, such as soil compaction and samples biased by an unrepresentative sampling of pores, that may limit their comparability with in situ measurements.[109] On the other hand, field techniques are based on time-consuming procedures and are more difficult to control, but they allow the estimation of more representative in situ soil hydraulic properties. Therefore, it is desirable to focus on simple field methods that can alleviate time-consuming constraints.[110,111] In conclusion, all methods have their pros and cons, and their selection mainly depends on the processes to be investigated and the temporal and spatial scales involved.

Runoff, soil losses, and sediment transport from the pedon to watershed scale

Soil erosion is a natural process driven by climate, topography, soil, and vegetation factors, which can be assessed using diverse methods depending on the spatiotemporal scale.[112,113] However, human activities (eg, deforestation, agriculture, changes in topography and landscape features) have been intensifying and even altering the natural dynamic and magnitude of soil particle detachment and redistribution, making these studies even more complex.[114] Since the first half of the 20th century, equations and indices have been developed as empirical approaches describing the complex hydrological response of soils to human

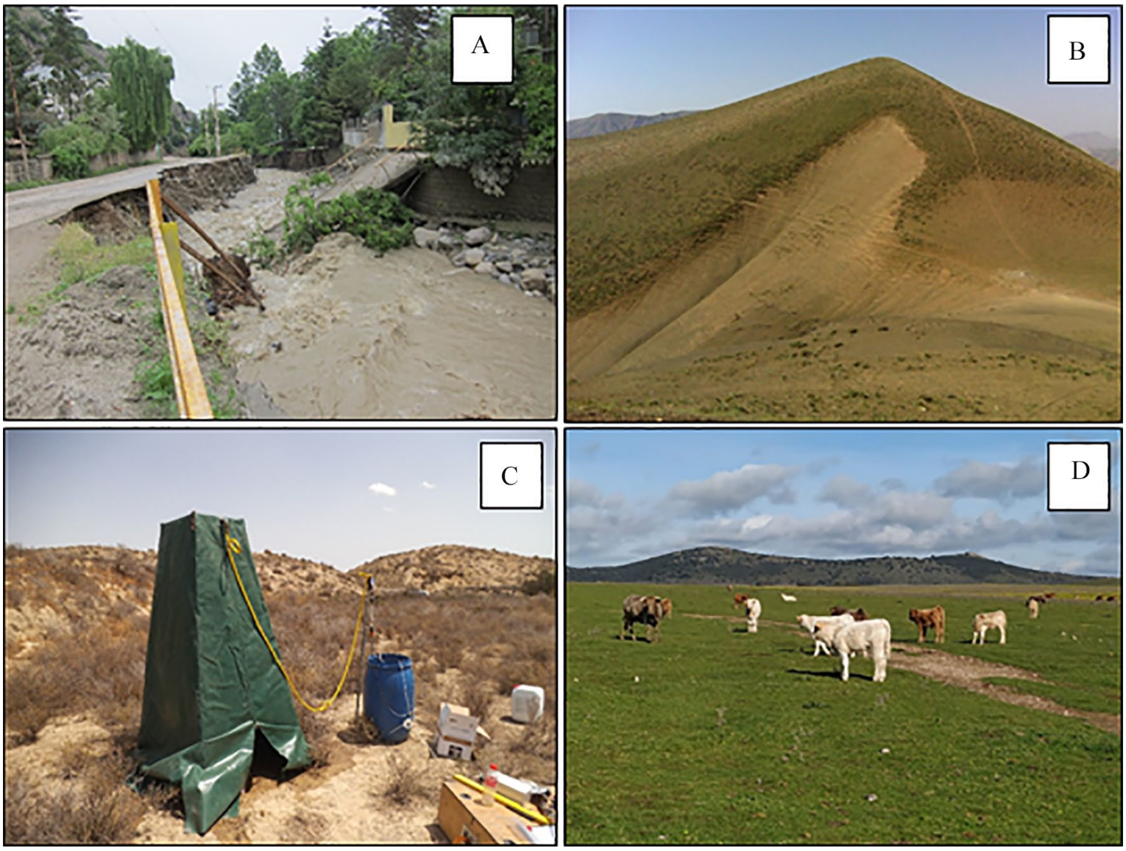

Figure 4. Soil erosion processes affecting urban, rural, and natural ecosystems: (A) floods in Mazandaran Province (Kelardasht), Iran; (B) landslides in Tehran, Iran; (C) rainfall simulation experiments in abandoned areas in SE Spain; (D) grazing areas of SW Spain. Photos were taken by Hamid Reza Pourghasemi (Shiraz University), Jesús Barrena and Manuel Pulido (Extremadura University), and Jesús Rodrigo-Comino (Valencia and Trier Universities).

activities and climate change.[115] Process-based model development enables us to integrate the knowledge of the natural and human-induced mechanisms and interactions among factors affecting runoff, using distinct approaches (eg, empirical, process-based and of mass or energy balance) and techniques (eg, GIS, remote sensing).[116] Some models allow the mapping of spatially distributed rates and patterns of runoff and soil redistribution.[117] Overland flow-mediated processes, such as soil and water pollution, flood prediction, landslide risk, and even crop yield can be also evaluated with these tools (Figure 4A and B). Also, models help assess the effectiveness/impact of soil and water conservation measures and agricultural, environmental, and climate policies.[118,119] Specific current challenges in the development and application of soil erosion models include (1 the non-linear relationships and thresholds between factors and processes; (2) the heterogeneity of model outputs obtained with different approaches at the same site; (3) the identification of stable areas; (4) the refinement of model predictions with accurate independent metrics of soil loss and deposition; (5) improved indicators of vegetation changes at a high temporal resolution using remote sensing; (6) upscaling model findings from the local scale to larger ones; and (7) integrating soil erosion processes with carbon sequestration, nutrient fluxes, diffuse contamination, and climate change scenarios.

From the pedon to the hillslope scales, natural hazards and human-induced disasters such as landslides, floods, and land-subsidence can cause damages ranging from severe financial losses to the loss of life and irreparable damages to ecosystems (eg, fragile water bodies, peatlands).[120,121] Preparing susceptibility, hazard, multi-hazard, and risk maps and assessments for an area of interest is key for scientists devoted to understanding soil dynamics and in helping land-use planners, managers, and decision-makers.[122,123] These assessments can be valuable for each community before, during, and after the occurrence of a given event. To accomplish this, statistical, probability, metaheuristic, machine learning, and ensemble-based GIS (geographic information system) and RS (remote sensing) models are being tested and improved in the most recent research studies.[124-126] However, the selection of the best model for application is challenging. There are various advantages and disadvantages to each of the above-mentioned algorithms. One of the most important problems with traditional models is related to the absence of precise border/class for categorical factors including lithological units, soil texture, and land use types in nature.[127] On the other hand, determining a natural border for continuous and numerical factors such as slope, elevation, distance from rivers, faults, and roads is very difficult, or even its mere description. So, determining natural disaster assessments with a high level of accuracy and considering simple effective factors that might predict natural disaster occurrence is an important previous step. In response to these issues, we can suggest machine learning approaches to increase model accuracy when dealing with complex and uncertain problems while also developing new methods and theories.[128]

On the other hand, conducting in situ measurements or field experiments is also indispensable to understand the activation of initial soil erosion processes and runoff results obtained under laboratory (controlled) or real (semi-controlled) conditions, as well as machine learning outputs. A rainfall simulator device, which is one approach to obtain such information, is shown in Figure 4C. To obtain meaningful results, experimental design procedures must be appropriate,[129] adequate, and standardized methods need to be used.[130] Enough events must be observed with sufficient repetitions to adequately characterize the system. The use of rainfall, wind, and runoff simulations[131] has to become a standard technique to confirm model applications or test plot variations at different points on hillslopes or in watersheds. Sediment tracers (eg, fallout radionuclides, rare earth elements, magnetic substances) allow the collection of erosion data that considers spatial distribution and the identification of sediment sources (fingerprinting), which is essential for characterizing soil erosion processes and validating soil erosion models.[132] Another hot topic is the use of biomarkers or biological indicators to understand past and current soil erosion and driving factors such as crusts or soil mobilization. Among these, dendrochronological methods and the improved stock unearthing methods are used in agricultural areas.[133-135] Finally, a new object of study is related to weather types and soil erosion, using erosion plots and accurate climate data.[136-138]

Watering ponds and soil quality due to livestock and overgrazing

Livestock husbandry is a key economic activity for both the survivorship of many rural areas and the preservation of cultural ecosystems with a high natural value (Figure 4D). Its sustainability depends on the efficient management of natural resources such as pasture and water through empiric knowledge of natural cycles (eg, climate, phenology of pasture species, livestock breeding).[139] The scarcity of fertile soils and water has traditionally been superseded by strategies based on animal movement (transhumance). Nowadays, many farms are self-sufficient because of the construction of watering ponds and conservation of grass, among other infrastructures and actions.[140] Nevertheless, this natural-based solution is also causing health problems due to a reduction in soil and water quality and transmission of diseases via wildlife.[141,142]

The origin of watering ponds is very ancient, probably from the times of the Roman Empire, although their broad dissemination is linked to the arrival of heavy machinery in the second half of the 20th century.[143] They are constructed to store water from different sources: direct rainfall and sub/surface runoff. They are designed taking into account geometrical parameters such as pond and basin surface, maximum depth, and so on. Marín-Comitre et al[144] summarized the hydrological response of different ponds to precedent rainfall. They concluded a pond must have a minimum surface of 2000 m^2 and a storage capacity rate of 100 m^3 ha^{-1} to guarantee water for livestock during drought periods. Other concerns for farmers and stakeholders include water quality in their ponds; more than 75% of them have admitted using water from wells under particular circumstances; these ponds also function as biodiversity preserves (eg, amphibians).[145]

Soil and water quality are key issues for livestock health and possible transmission of diseases from animals to humans via meat consumption because of pathogens and chemical residues present in low-quality water, soil, and plants.[146] This quality largely depends on appropriate land management because overstocking animals can produce an increase in soil erosion and compaction and loss of biodiversity and soil organic carbon,[147,148] meaning more contaminants arrive in surface water. In addition, livestock is considered a major water polluter because they can defecate directly into the pond and their excreta can arrive in water via runoff.

Some countries with a long farming tradition (eg, the United States, Argentina, Australia, New Zealand, South Africa) have developed specific legislation to guarantee water quality for consumption by their livestock and, subsequently, for soil/water interactions. The EU (Regulation (EC) No 183/2005—requirements for feed hygiene) only mentions that water for animals should have the same quality as for human consumption, but it does not provide any information about indicators that can be assessed by farmers (*E coli*, nutrient contents, color, the turbidity of the water, etc) despite the 30 directives and regulations which have set up the EU policy to limit degradation and pollution of aquatic environments since 1975 (eg, directive 2000/60/CE).

Therefore, further research on soil and water for livestock from different perspectives is still needed. It is relevant to pay attention to how the water for livestock, stored in watering ponds, moves through soil and how soil influences the quality of water in the pond, both as a potential source of contaminates and as a filter system. Some important research questions have not been solved yet include (1) how exactly soil management influences the amount and quality of the stored water, (2) will the current infrastructures be able to face future challenges in soil management caused by climate change, and (3) which parameters should be used as indicators of soil quality and the quality of water and plants used for animal consumption?

Digital Soil Mapping (DSM)

Soil maps support many research fields including, but not limited to, pedology, soil classification, soil survey, landscape modeling, natural resources management, land use planning, carbon storage, land use/land cover change, and environmental risk assessment.[149-152] Numerous assessments have defined and criticized current soil mapping techniques.[1,153,154] DSM involves 3 main components: (1) input data (field and laboratory soil observations), (2) the process (building mathematical or statistical models to better fit the soil-environment relationships), and (3) output (continuous thematic or raster maps), and the associated uncertainties. The first recognized soil maps were produced in the mid-19th century to determine the suitability of land use for agricultural purposes. Vast growth occurred in this field in the 20th century due to the development of computers and information technology,[130-132] including exponential development in geographic information systems (GIS), global positioning systems (GPS), remote sensing (RS), and geostatistics. The availability of satellite images, digital elevation models (DEMs), Light Detection and Ranging of Laser Imaging Detection and Ranging (LIDAR), and radio detection and ranging (RADAR) are key to understanding the increasing research on digital soil mapping. The utilization of proximity sensors such as portable X-ray fluorescence (PXRF) spectrometry, gamma-ray radiometry, UV-visible fluorescence measurements, and visible near-infrared reflectance (Vis-NIR) spectroscopy, as well as computational algorithms, represent new horizons to be explored.[155-162]

The availability of soil maps is fundamental to underpin sustainable soil management decisions at local, regional, national, and global scales, but currently faces 3 main issues: (1) soil surveys, carried out either conventionally by experienced pedologists and/or using DSM approaches,[163,164] are still far from covering many parts of the planet, particularly at detailed scales higher than 1/50 000; (2) soil surveys are costly and time-consuming, therefore they are scarce; and (3) several soil properties, such as topsoil nitrogen content, may vary over short to medium temporal ranges (5-10 years) and need to be periodically updated. Over the last two decades, DSM has gained more and more recognition linking field, laboratory, and proximal soil observations with quantitative spatial and geostatistical methods to infer soil spatial patterns.[165] The GlobalSoilMap program, which aims to provide a fine resolution global grid of soil functional properties, is emblematic of the challenges raised by DSM.[163] In addition to specifications to harmonize soil profile properties (eg, by using spline functions[166]), it has provided international standards for output maps, including the requirement of estimates of the uncertainties associated with mapped properties.[167-169] The availability of increasing amounts of remote sensing data, notably the Sentinel satellite series, is promising for enabling not only updates to existing maps but also a wider coverage of digital soil maps of soil properties. Remote sensing reflectance spectra of bare soil pixels are likely to predict several topsoil properties[170] while reproducing spatial structure[171-174] and may also contribute to infer uncertainty.[175] To date, few authors have incorporated satellite imagery as covariates within DSM models.[176] As the widely available Sentinel-2 series have recently exhibited promising capacities to predict soil properties spectrally,[177-180] this is a new challenge for the coming years.

Soil Organic Carbon Sequestration in Climate-Smart Agriculture

Need for soil organic carbon sequestration

Soil degradation, which includes several processes such as soil erosion, salinization, acidification, compaction, nutrient depletion, and soil organic carbon (SOC) depletion, is a threat to soil fertility (Figure 5A), and hence, food security—especially in developing countries.[181] Currently, 33% of global soils have lost much of their SOC through the historical expansion of agriculture and pastoralism.[182] This has resulted in increased erosion risks and reduced water storage and nutrient supplies. However, this trend may be reversed by implementing management practices that enhance soil carbon sequestration by increasing C input or reducing C losses from the soil. In agriculture, several practices (such as green manuring, increased cereal use in rotation schemes, use or substitution of mineral with organic fertilizers, the use of organic amendments (Figure 5B), crop residue incorporation and reduced tillage) provide a valuable alternative to conventional systems, without compromising food production.[183,184]

The sequestration of SOC has become part of the global carbon agenda for climate change mitigation and adaptation through the launch of the "4 per mille" initiative at COP21 by UNFCC in Paris in 2015. The idea behind the initiative is that an annual increase of 4‰ of the global SOC stocks in the top 0.3 to 0.4 m of all non-permafrost soils would counteract the annual global rise in atmospheric CO_2.[185] Increases in SOC are, however, only realistic in actively managed soils including agricultural soils and managed forestry in the first 0.3 to 0.4 m soil depth. This would require an annual increase of 4.7 Gt C y^{-1} in agricultural soils to compensate for the net annual increase of atmospheric C, averaged over the years 2005 to 2014.[186] Various studies estimated the technical potential for SOC sequestration and, in a broader sense, SOC storage171 by improved (1) cropland and grazing land management, (2) livestock and manure management, (3) restoration of degraded lands and cultivated organic soils, and (4) agroforestry.[187-191] Global-scale SOC sequestration rates have thus been estimated at 2 to 3 Gt C y^{-1}, but those estimates are likely far too high due to a lack of nutrients like N and P necessary to sequester the suggested amount of carbon in extensive grasslands and croplands with low fertilization rates. This follows from stoichiometric considerations, ie, the need for sequestering N and P given the C/N and C/P ratios in stored SOC.[192,193] Despite its limitations and the need for further research, the implementation of management practices that increase SOC contents can improve soil quality, fertility, and functioning.

Challenges for soil organic carbon sequestration

The major potential for significant carbon sequestration is in the world's cropland soils, especially in those with large yield gaps[191] and/or large historic soil organic carbon (SOC)

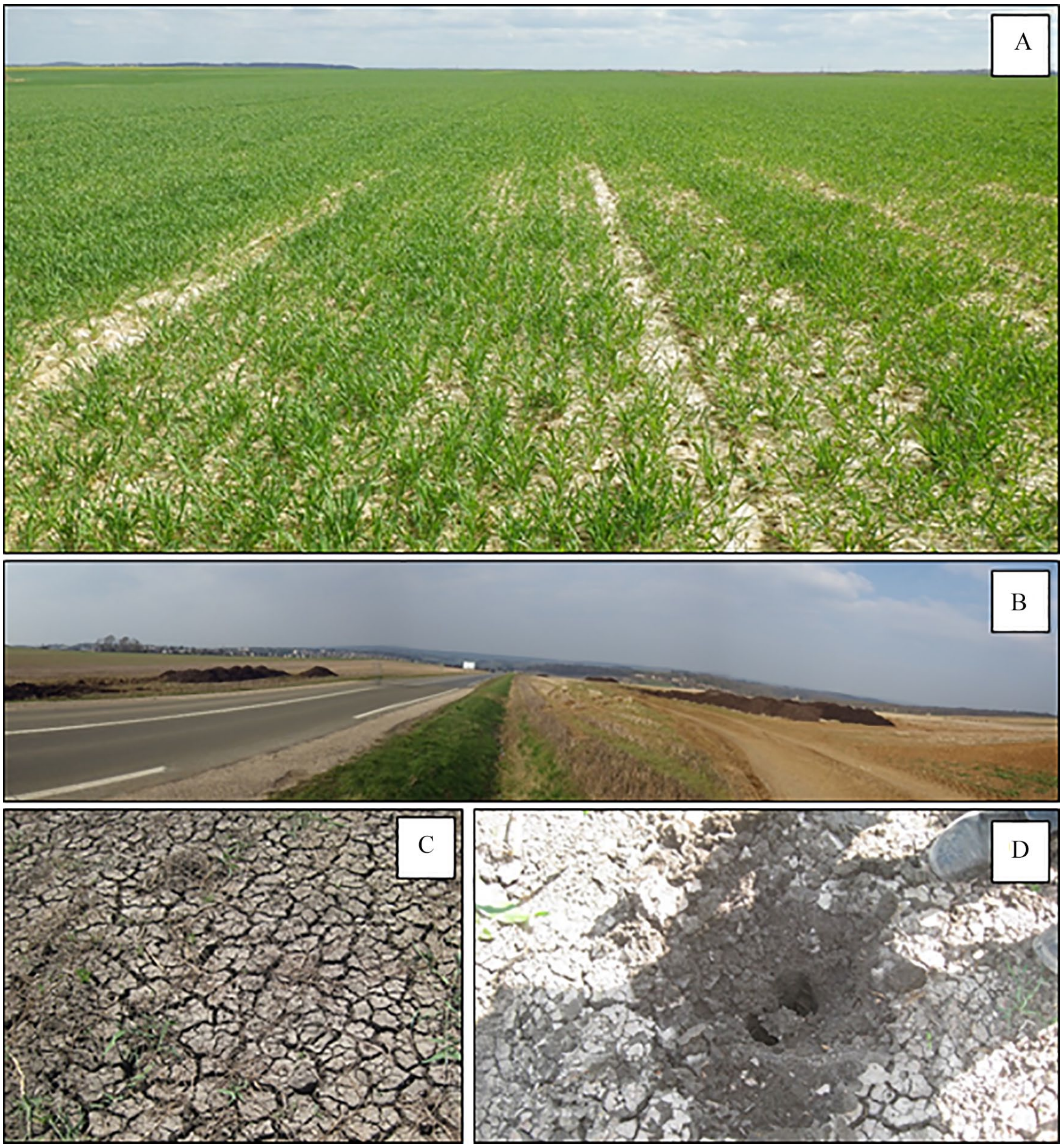

Figure 5. Need for soil organic carbon storage: (A) differences in winter wheat development due to the presence of a slaking crust in Luvisols1 from loess with low topsoil organic carbon content; (B) green waste compost about to be spread over fields; (C and D) salinization processes, Northern Nile Delta, Egypt. Photographs taken in the Versailles Plain (France) by Emmanuelle Vaudour (AgroParisTech) and Noura Bakr (National Research Centre, Cairo).

losses.[182] Closing the gaps between the current and water-limited yields can be achieved mostly by a more balanced nutrient supply, which is intimately linked to SOC sequestration, by enhanced crop residue return in support of SOC sequestration.[183,194] Rising SOC values may also increase agricultural yields in areas with low SOC or high salinity (Figure 5C and D) contents due to associated improvements in nutrient supplies, water-holding capacity, and soil structural stability.[195,196] However, there is a price to SOC sequestration as it also implies immobilization of N in SOC and the elevated N inputs that are needed to enhance plant uptake and N immobilization may cause trade-offs with nitrous oxide (N_2O) emissions.[197,198] The challenge is to close the yield gap sustainably, with low N_2O emissions, to contribute to climate change mitigation. This calls for a spatially diversified strategy for climate change mitigation from agricultural soils, focusing on efforts to (1) improve N use efficiency and reduce N_2O emissions in soils with a low C sequestration potential and (2) sequester carbon in soils with a low C stock and a high C sequestration potential.[192]

Conclusions

This review aimed to present and discuss some challenges and possible ideas associated with recent advancements in soil research. Twenty experts belonging to the editorial board of *Air, Soil and Water Research* gave examples that illustrate some of the diverse and complex problems that affect soils. A summary of the main conclusions is shown in Figure 6, where a pyramidal diagram shows the main threats and challenges

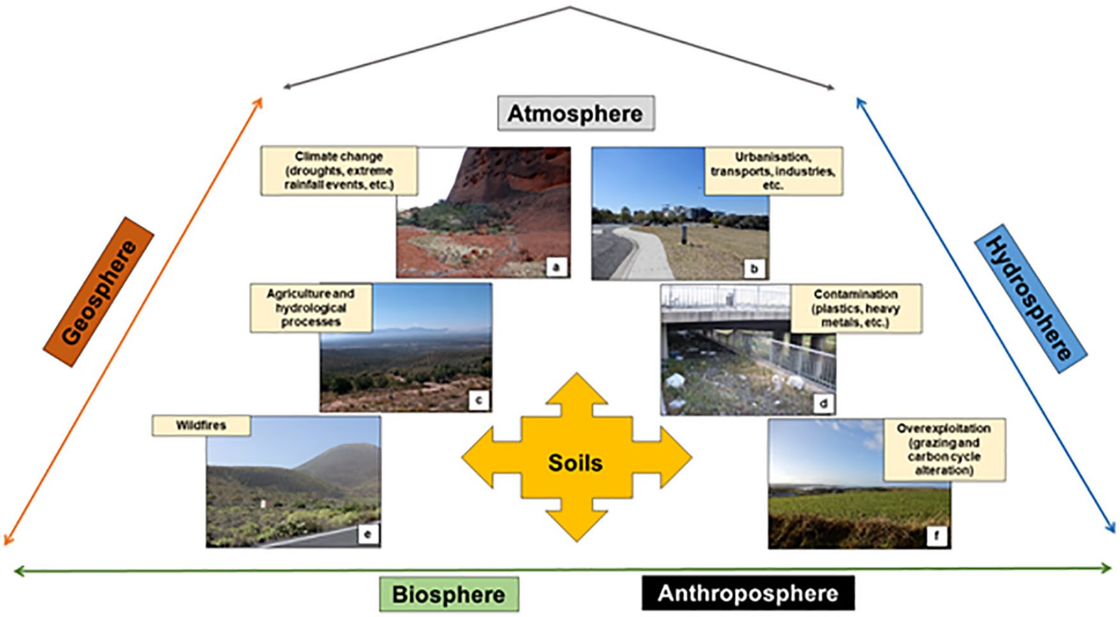

Figure 6. Pyramid representing the interconnections between soils and ecosystem spheres, and showing threats and challenges to be solved: (A) Uluru/Ayers Rock, Australia; (B) urban soils in Canberra, Australia; (C) olive orchards, Sierra de Mágina mountains and abandoned areas, Jaén, Spain; (D) Guadalmedina River with plastics, sediments and urban soils, Málaga, Spain; (E) wildfires, Canary Islands, Spain; (F) grasslands, Northern Ireland. Photos were taken by Jesús Rodrigo-Comino (Valencia and Trier Universities).

discussed in this article. Many of the soil-related challenges (compaction, erosion, contamination) have been around for decades and the underlying processes have been studied extensively by the scientific community. New aims are primarily the technologies that became available and affordable over the last few decades (computational capacities, GIS, remote sensing, bioremediation techniques, etc) that provide us with new opportunities to better address some of these challenges. Emerging new technologies based on geographic information systems and remote sensing combined with models, new computational capabilities and algorithms or in situ measurements provide new opportunities to understand soil processes and interactions at diverse spatiotemporal scales. Micro-plastics are an emerging potential pollutant with the potential to negatively affect the world's soils, and now are even more relevant due to the residues of face masks (produced from polymers) used during the COVID-19 pandemic. Still, studies on micro-plastics in soil systems are scarce; therefore, it highlights the urgent need for future studies to fill the important knowledge gaps related to microplastics in soil systems. Also, more research must be conducted, especially in field conditions and over the medium to long term, on the development and application of green technologies to mitigate pollution and other degradation factors of soils. Impacts from wildfires and human activities (urbanization, industrialization, transportation, agriculture) on soil microorganisms (biodiversity) and thereby on biogeochemical cycles, especially organic carbon, nutrients and pollutants, and water availability should be major objectives of the investigation by the scientific community. Data sharing and more open data access between soil scientists are also important. This can further facilitate modeling, increase knowledge and accelerate collaboration between peers. All the above topics and more are important and related to the influence of soils on human health. Manuscripts on these emerging topics are highly welcomed in *Air, Soil and Water Research*.

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We thank the scientific community cited in this review and other researchers who are trying to understand soils. This article is dedicated to all the stakeholders who are facing delicate environmental situations characterized by climate change, water and soil degradation, migration from rural and marginal areas, and non-deserved low prices and incomes for their produced resources and goods.

Author Contributions

All authors contributed equally to this work.

ORCID iDs

Jesús Rodrigo-Comino https://orcid.org/0000-0002-4823-0871

Manuel López-Vicente https://orcid.org/0000-0002-6379-8844

Vinod Kumar https://orcid.org/0000-0001-6142-1026

Andrés Rodríguez-Seijo https://orcid.org/0000-0003-4868-3069

Claudia Rojas https://orcid.org/0000-0001-7727-2862

Hamid Reza Pourghasemi https://orcid.org/0000-0003-2328-2998

Eric C Brevik https://orcid.org/0000-0002-6004-0018

Maja Radziemska https://orcid.org/0000-0002-3526-5944
Manuel Pulido https://orcid.org/0000-0001-9340-0107
Simone Di Prima https://orcid.org/0000-0002-5066-3430
Erika S Santos https://orcid.org/0000-0002-3664-839X

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